ABSTRACT

In cooperation with NASA's Solar System Exploration Subcommittee and its working groups, JPL is studying planetary science missions proposed for launch near the end of the next decade. Results will focus resources on developing technologies that enable a set of missions in which extraordinary scientific advances reward meeting severe technological challenges. This paper describes Saturn Ring Observer (SRO), an innovative, chemical-propulsion-only approach to a previous mission concept that enables close-up observation of Saturn's rings to obtain fundamental new information about ring dynamics, some relevant to planetary system formation. It describes the mission's science goals, provided by the Astrophysical Analogs in the Solar System Campaign Strategy Working Group, and the resulting mission concept.

The primary goal is understanding ring processes and evolution as a model for the origin of planetary systems. This involves direct observations of kinematic processes and parameters in the rings, direct observations of the physical nature and distribution of the particles, measuring local surface mass density over a wide radial range, and mapping the optical depth profile at high (~10 m) radial resolution and at several co-rotating longitudes.

The ring opening angle as seen from the approaching spacecraft sets an arrival time window at Saturn. Saturn orbit insertion uses a single-pass aerocapture followed by direct insertion near the Huygens gap at apoapsis. The science mission concept calls for placing the spacecraft in a ring-particle-like orbit with a very small inclination; frequent small plane-change maneuvers enable "hovering" 3 ± 0.5 km removed from the ring plane. One month of science operations follow insertion, with as many as four changes in radial position totaling several thousand km.

INTRODUCTION AND BACKGROUND

Early spacecraft exploration of Saturn's rings revealed a rich set of physical phenomena that cannot be duplicated or imitated in current Earth-based laboratories. These phenomena are intimately tied to subjects of fundamental importance such as the long-term stability and evolution of ring systems, and the behavior and evolution of protostellar and protoplanetary accretion disks. Details of many of the large-scale phenomena we see, such as shepherding by satellites, creation of ringlets, eccentric ringlets, propagation of waves through the rings, etc., depend on the microphysics of individual particles and small agglomerations of particles. Lack of accurate knowledge of particular microphysical parameters hinders researchers attempting to investigate planetary system formation by modeling the evolution of protoplanetary disks. Notably, particle shapes, spin states, and collisional coefficients of restitution are essentially unknown. Rates of dust generation during collisions and subsequent reagglomeration are also unknown. Particle size distributions and collision frequencies in the solar system's known ring systems are only loosely constrained. Measurement of these parameters would immediately enable great advances in our understanding of planetary system formation and ring system evolution.

Since these phenomena and their associated parameters do not lend themselves to laboratory measurements, the best means of measuring them are to observe them directly in the best natural laboratory available: Saturn's rings. Scientists have envisioned close-up observation of Saturn's rings, from distances of a few km, for at least 30 years[1]. Space flight mission designers have attempted mission designs to accomplish those observations for nearly that long. But the energetics of transfer from Earth to Saturn, and insertion into an orbit at Saturn that enables the needed observations, call for extremely high mission ΔV. Even ignoring the interplanetary transfer and considering only direct propulsive transfer from hyperbolic approach to Saturn orbit at about 2 Saturn radii, the ΔV is in the range of 8-10 km/s, clearly beyond the capabilities of current or envisioned chemical propulsion systems. Previous mission designs met this challenge by using Nuclear Electric Propulsion[1,2] (NEP). NEP's combination of high I_S and high power made it a good match to the mission requirements. Unfortunately, the current programmatic climate makes NEP infeasible for the foreseeable future. This paper outlines a mission design for a Saturn Ring Observer (SRO) mission that has Saturn itself provide the bulk of the ΔV necessary for orbit insertion, with the remainder within chemical propulsion capability.

The Saturn system's geometry requires greater care than usual in avoiding impact hazards. Figure 1 illustrates the gross structure[3]. Rings easily visible from Earth, A, B, and C, are an essentially continuous distribution of material from 74,500 to 136,780 km from Saturn's center, broken by narrow gaps such as the

Cassini Division, from 117,510 to 122,050 km, and the Encke Gap, from 133,410 to 133,740 km. In order of greatest average surface mass density to least, they are: B, A, C. The narrow F ring is an eccentric, "kinky" ringlet at 140,200 km. A broad gap extends from there to the G ring inner edge at 170,180 km. At about 178,500 km the G ring transitions to the E ring, which has a very diffuse outer edge around 300,000 km. Interior to the C ring is the D ring, with much lower surface mass density than the C ring (but nonetheless a significant spacecraft hazard). Although the inner edge of the D ring is officially placed at 67,000 km, current ring dynamics theory predicts material spreading inward all the way from there to the upper reaches of Saturn's atmosphere[4,5]. Rings A, B, and C are tightly constrained to Saturn's equatorial plane, with particle excursions from that plane being about 1 km or less[6]. The greatest excursions are thought to be due to wave phenomena in the rings. The particles appear to be mostly macroscopic, with most in the range 10 cm to 1 km and very few less than 1 cm. Rings D and F appear to have more dust. The G and E rings are more diffuse, with a much greater thickness out of the equatorial plane; particle sizes there are generally microscopic.

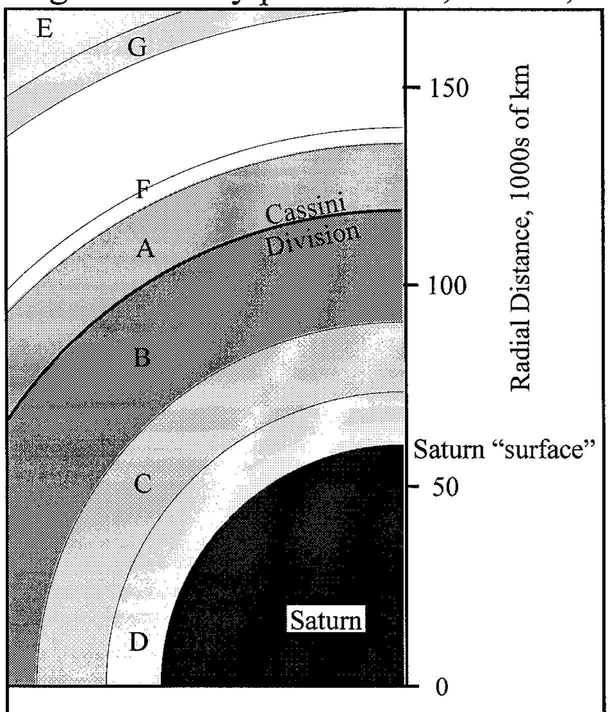

Figure 1: Radial structure of Saturn's rings

SCIENCE OBJECTIVES AND REQUIREMENTS

In preparation for an SRO mission study[7] by JPL's "Team X," the Astrophysical Analogs in the Solar System Campaign Science Working Group (AACSWG) derived the mission's science and measurement objectives, prioritizing them into three categories:

1.A (minimum mission, unique) Determine the physical nature and kinematics of ring particles and agglomerations of particles.
Measurement Objectives:

- Make direct observations of microphysical kinematic processes and parameters in the rings, including:
  1. Random velocity components in all three directions
  2. Ring scale height, related to V_Z
  3. Coefficient of restitution in typical collisions
  4. Clumping/sliding/shearing behavior of agglomerations, preferably in the A ring
  5. Particle spin states
- Make direct observations of the physical nature and distribution of the particles--shape, roughness scale, particle size frequency distribution in the 1 cm to 1 km range (including possible size segregation effects)--across several (at least three) diverse regions. Regions of interest include density and bending waves, a sharp satellite-shepherded edge (e.g., the outer edge of the B ring), and a narrow eccentric ringlet like the Huygens ring to test density/bending wave models and shepherding theory predictions.

1.B (mission enhancing, unique) Determine the mass distribution and optical depth over a wide radial range and azimuth. Collect data to test models of wave production, shepherding, and ring confinement.

2.A (mission enhancing, extension of Cassini) Determine the electromagnetic environment of the rings, in particular in the spoke region. Determine the distribution of dust. Determine the distribution of the ring's neutral and ionized "atmosphere."

(Note: specific measurement objectives are listed only for the 1.A science objectives)

Instrumentation

Highest priority is given to narrow- and wide-angle imaging. The narrow-angle instrument should provide approximately cm-scale resolution from a distance of about 3 km. The wide-angle imager should have a 60° field of view. Next in priority is a radar or lidar altimeter with a 30° field of view, also needed for near-ring navigation and maneuvering. These instruments accomplish the 1.A and 1.B objectives. Adding an ion/neutral mass spectrometer, a magnetometer/electric fields instrument, and a dust detector accomplishes the 2.A objectives.

Science-Based Mission Design Requirements

To avoid collisions with ring particles the SRO basic spacecraft should orbit Saturn about 3 km out of the ring plane, "hovering" and corotating with ring particles in very nearly circular orbits directly "beneath" it. Optical measurements and communications require that the spacecraft be on both the sunlit and Earth-facing side of the ring; large ring-opening angles that facilitate the measurements ensure no conflict here. Fulfilling the requirement to observe diverse regions of the rings involves adjusting the orbit radius by several thousand km in three or more steps. Time required to characterize each region indicates an on-station mission duration of at least 30 days.

IMPLEMENTING THE DESIRED SATURN ORBIT

Requiring an orbit that "hovers" out of the ring plane immediately implies a non-Keplerian orbit, which for this application are known to be stable[9]. At a largely spherical object like Saturn, this further implies energy expenditure to maintain the orbit. Figure 2 contrasts the orbits of an object in an unmodified Keplerian orbit and one in the directed, non-Keplerian orbit needed for SRO. As seen from the ring plane, an object co-orbiting but initially offset from the ring plane by some distance h experiences an apparent axial force toward the ring plane. Movement of the object toward the ring plane due to this apparent tidal force is actually a manifestation of the object's natural Keplerian motion in an orbit inclined with respect to the ring plane, which must intersect the ring plane twice each revolution. To maintain the non-Keplerian orbit, the spacecraft must counter that apparent force propulsively.

Constant-Force Solution

Approximating Saturn as spherical, calculating the magnitude of the axial force is straightforward. Differentiating Saturn's gravitational acceleration field at the equatorial plane with respect to axial separation yields the expression for the apparent acceleration toward the ring plane:

$$\left|\vec{a}_{ax}\right| \approx -\frac{\mu_{sat}}{r^2}\left[\frac{h}{r}-\frac{1}{4}\left(\frac{h}{r}\right)^3\right] \tag{1}$$

where h is the axial offset distance, r is the orbit radius from the center of Saturn, and μ_{sat} is Saturn's gravitational parameter. If the offset is not entirely axial, but is instead slightly inward such that the radial distance of the point in the plane and the offset point are exactly the same, Eq. 1 is exact. If the offset is entirely axial, then higher order terms in h/r exist. Since in this case h/r is of order 1/40,000, the second term and any higher order terms of Eq. 1 are insignificant, so the axial acceleration can be approximated

$$\left|\vec{a}_{ax}\right| \approx -\frac{\mu_{sat}h}{r^3} \tag{2}$$

There is also an apparent acceleration in the radial direction, but it is of order $(h/r)^2$ and can be compensated by a tiny change in radial position. The force necessary to cancel the axial acceleration has the opposite sign and, true to F=ma, is proportional to spacecraft mass M_{SC}:

$$F \approx \frac{\mu_{sat}h}{r^3} M_{SC} \tag{3}$$

Eq. 1 also leads directly to ΔV requirements for sustaining the orbit for a duration of Δt:

$$\Delta V \approx \frac{\mu_{sat} h}{r^3} \Delta t \tag{4}$$

Given a propulsion system with an effective specific impulse of I_S, the propellant use rate is

$$\dot{m} \approx \frac{\mu_{sat}}{I_S \cdot g} \frac{h}{r^3} M_{SC} \tag{5}$$

where g is Earth's surface gravitational acceleration. A constant-force solution has the advantage of yielding the minimum propellant consumption rate for a given minimum offset.

For a 100-kg spacecraft offset 3 km from the rings at r=125,000 km, the required force is about 6 mN. If we could provide this force with an effective I_S of 300 s, a hovering-propellant mass fraction of only 10% yields a duration of about two months. But this is in an awkward thrust range for practical propulsion systems: it is too small for accurate and efficient constant-thrust chemical systems and too large for FEEP thrusters. Cold-gas systems have characteristically low I_S, providing insufficient mission duration for reasonable propellant mass fractions. Current and proposed ion thrusters operate inefficiently at this level, but even given an optimally-sized custom ion thruster, the electric power needed is problematic. Given the 100-kg example above, a 6 mN ion thruster operating at an I_S of 3000 s requires about 180 W *before* considering power supply and conditioning inefficiencies. If the spacecraft uses 100 W, total power needs require at least two and probably three AMTEC units, making more than half the spacecraft mass AMTEC units. Currently this thrust magnitude problem is the main disadvantage of the constant-force solution.

Pulsed Solution

A solution to the mismatch between typical chemical engine thrusts and the force needed for the constant-force case involves pulsing the engine(s) and allowing the ring offset to vary with time. Establishing the minimum offset h_{min}, begin with a spacecraft co-orbiting at offset h_{min}. The engines burn for a short time, imparting a small axial velocity away from the ring. Tidal acceleration gradually decreases this axial velocity to zero, at some offset h_{max}, as the spacecraft orbits. The spacecraft's motion after the burn is exactly that of an object in a natural Keplerian orbit with a small inclination with respect to the ring plane. After reaching h_{max}, it continues accelerating slowly toward the rings until again approaching h_{min}. The engines then burn again, starting a new cycle of ascent to h_{max} and descent to h_{min}. The next cycle's motion is again exactly that of an object in a Keplerian orbit with a small inclination with respect to the ring plane, but in this second cycle the maneuver has shifted the node longitude by an amount equal to the longitude traversed in the first cycle. Orbital plane changes often involve much ΔV, but these inclinations are so tiny that the plane change from one cycle to the next involves small ΔV, of the order 1 m/s. Each burn can be considered a short-duration "bounce" at the plane $h = h_{min}$. Figure 3 illustrates the shape of such an orbit with four burns per revolution. Seen from above Saturn's pole, the orbit would appear circular.

Propellant use estimates for such orbits necessarily depend on the number of burns per orbit, n. Assuming a repeating orbit such that n is an integer, values of n less than 3 allow the spacecraft to reach or penetrate the ring plane, so $n \geq 3$. The ΔV at each burn is given by

$$\Delta V_n = 2h_{min}\sqrt{\frac{\mu_{sat}}{r^3}}\tan\frac{\pi}{n} \tag{6}$$

For the spacecraft used in the constant-force analysis, n=4 yields each $\Delta V \approx 0.84$ m/s. Assuming 10 N of thrust, each burn's duration is less than 10 s, far less than the period between burns. Distributing n such burns over the orbit period yields the time-averaged propellant use rate:

$$\dot{m} = \left(\frac{n}{\pi}\tan\frac{\pi}{n}\right)\frac{\mu_{sat}}{I_S \cdot g}\frac{h_{min}}{r^3}M_{SC} \tag{7}$$

This is the same result as the constant-force case for $h = h_{min}$, modified by a factor involving n. It is easily demonstrated that as n approaches ∞, Eq. 7 approaches Eq. 5. For n=4 the first factor of Eq. 7 is ~1.27, so use of the pulsed approach carries less than 30% propellant penalty; that choice of n also has $h_{max} = \sqrt{2}\, h_{min}$, so the variation in offset with time is not extreme. Propellant penalty and h variability decrease as n increases. There is no fundamental requirement for the averaged number of burns per orbit to be exactly integral. The pulsed strategy allows the same engines used for bounces to handle changes in orbit radius, saving propulsion system inert mass. Standard quasi-Hohmann transfers, slightly out of the ring plane, perform those radial excursions.

INITIATING THE NON-KEPLERIAN ORBIT

Both the preceding orbit strategies start with a spacecraft co-orbiting with ring particles, offset from the ring plane by h. Delivering the spacecraft to that state is certainly a non-trivial task. For example, assuming a hyperbolic approach slightly inclined to Saturn's ring plane with V_∞ about 6 km/s and periapse at the target radius of 2 Saturn radii, the single-impulse ΔV required is 8.1 km/s, comparable to launch from Earth's surface to LEO.

Aerocapture offers the advantage that the planet itself provides most of the ΔV. But aerocapture at Saturn is significantly constrained by the ring collision hazard: the spacecraft must not enter or cross the ring plane between the far upper atmosphere and about 2.6 Saturn radii. The constraint is satisfied if the spacecraft is in the process of aerocapture, immersed in Saturn's atmosphere, as it first crosses the ring plane.

Figure 4 illustrates a mission design based on such an aerocapture. The spacecraft's hyperbolic approach, inclined slightly with respect to the ring plane (less than 5°) such that approach is on the shadowed side of the rings, delivers it to the atmospheric interface before reaching periapse, at a speed of 36 km/s. Deceleration, a total of 7.1 km/s, is performed via ballute or lifting body aeroshell. The Team X study opted for a ballute, with a mass of 25% of the total entry mass. The bulk of the deceleration occurs well into Saturn's stratosphere, where density variations are not as great as those in the upper atmosphere. Nominal exit occurs on the lit side of the rings (periapse is near the ring plane) and has the line of apsides aligned with the line of nodes, with apoapse at the target radius for the initial observing orbit. Onboard navigation during aerocapture is critical, required both to determine the time for ballute jettison and to accurately determine the deviations of the exit state from nominal, which in velocity may be sizeable, as much as 500 m/s[8]. Immediately after exit the spacecraft performs an autonomous clean-up TCM that accurately targets apoapse, using a high-thrust propul-sion stage that also performs Saturn approach TCMs (ΔV ~50 m/s) and the circularization burn just before apoapse (ΔV ~3.1 km/s for insertion over the B ring, just inward of the Cassini Division), nearly four hours after exit. The final moments of the circularization burn can be done with less than 100% engine duty cycle, using the altimeter to measure range to the rings, assuring a smooth transition to the initial hovering state. At this point the stage is jettisonned, soon to become another ring particle. Hovering engines on the basic spacecraft perform all subsequent maneuvers. In this case this strategy reduces the propulsive requirement for insertion into the initial hovering orbit from ~8 km/s to ~3.7 km/s, shifting most of the burden onto the ballute.

Other Options

The strategy outlined above offers the minimum propulsive ΔV requirement but involves more risk than a direct-insertion strategy. Several critical events must occur in a relatively short time, most based on autonomous decisions. Other options reduce that risk by increasing the time from exit to hover insertion, but all carry ΔV penalties, some sizeable.

One example decreases the aerocapture ΔV, placing apoapse in the gap between the F and G rings. A maneuver there raises periapse to the target hover location where circularization occurs. The net effects are: increase the time between exit and hover insertion to ~12 hours, long enough to allow ground participation (but with another maneuver between); decrease aerocapture ΔV to ~5 km/s; and increase propulsive ΔV to ~4.5 km/s. The increased propulsive ΔV is a distinct disadvantage because it now requires another propulsion stage, with its additional inert mass.

Another strategy, a variant on the first, reduces risk by having the periapse raise maneuver place periapse in the F-G gap also, so the spacecraft is in a "safe" orbit that can be maintained until a ground decision to proceed. The final orbit is achieved by a quasi-Hohmann transfer to the target location and then circularization to the hover orbit. Unfortunately, this strategy's propulsive ΔV jumps to a minimum of ~ 6 km/s, requiring two full stages and representing a significant fraction of the direct insertion ΔV.

Size limits do not allow here an exhaustive discussions of options examined to date. Options not discussed include multiple aerobraking passes after aerocapture, passing through the ring plane through one of the gaps, various means of Earth-to-Saturn transfer, and others. Work continues at JPL to refine this concept, which the Solar System Exploration Subcommittee includes in its list of high-priority long-term (launch after 2007) missions.

CRITICAL TECHNOLOGIES

The Saturn Ring Observer mission is a demanding mission that requires significant technological advances in several areas. Propulsion costs dominate mission cost estimates for SRO, currently near $600M. Driving down propulsion costs, a key facet of the strategic technology program, will benefit many low-cost missions. Other SRO technology needs would immediately enable whole classes of missions. The primary SRO technology drivers identified so far are:

1. Aerocapture at Saturn, either ballute or lifting-body aeroshell
2. Autonomous navigation both during aerocapture and in free orbit
3. Autonomous maneuver design and execution, for hover orbit insertion and station-keeping
4. Advanced interplanetary propulsion, such as advanced SEP or solar sail
5. Light-weight, low-power spacecraft systems
   a. Avionics
   b. Multifunctional structure
   c. Improved Advanced Radioisotope Power Supplies (ARPS)
   d. Data compression and high data rate communication
   e. Smart thermal control

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FIG. 2: "HOVER" ORBIT GEOMETRY, CONSTANT-FORCE SOLUTION

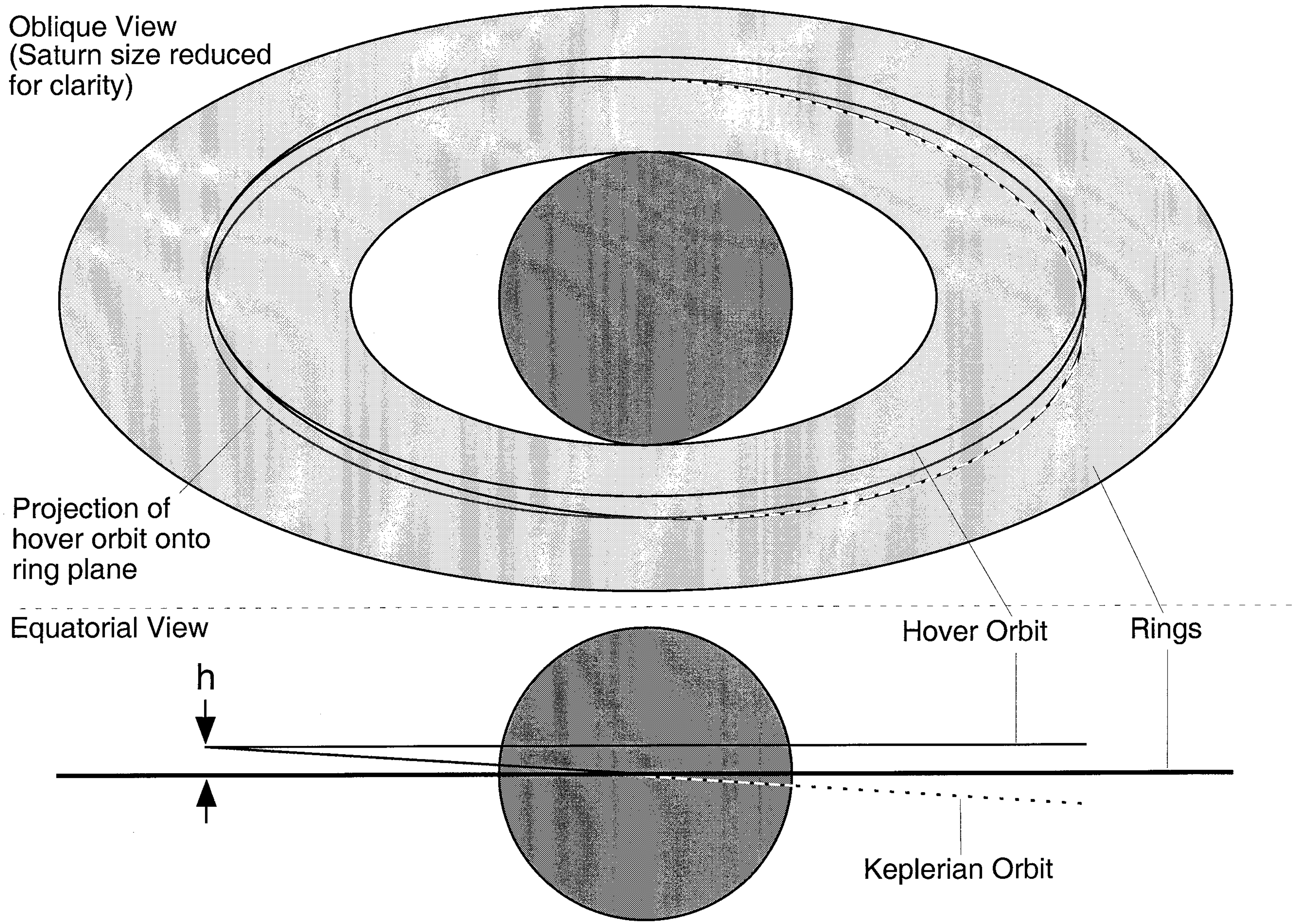

FIG. 3: PULSED SOLUTION "HOVER" ORBIT, n = 4

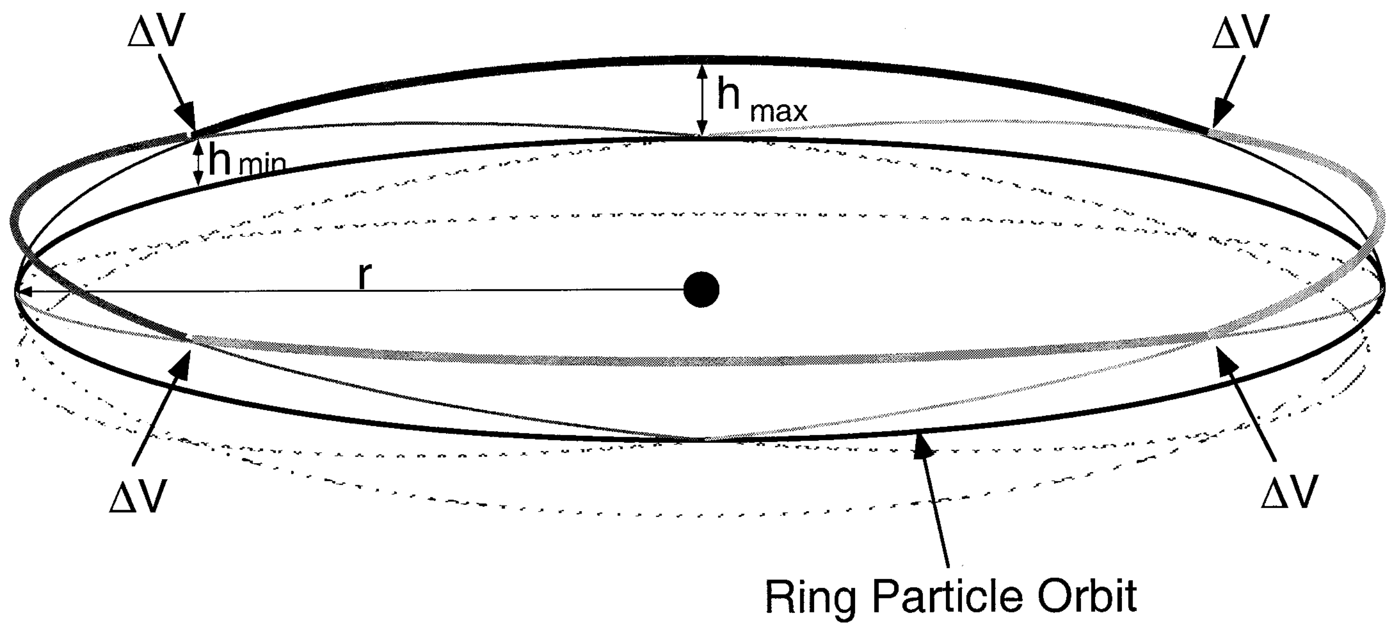

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FIG. 4: DELIVERY USING ONE PROPULSIVE MANEUVER